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National Aeronautics and Space Administration

NASA

Overview of a Proposed Flight Validation of Aerocapture System Technology

In-Space Propulsion Technology Project

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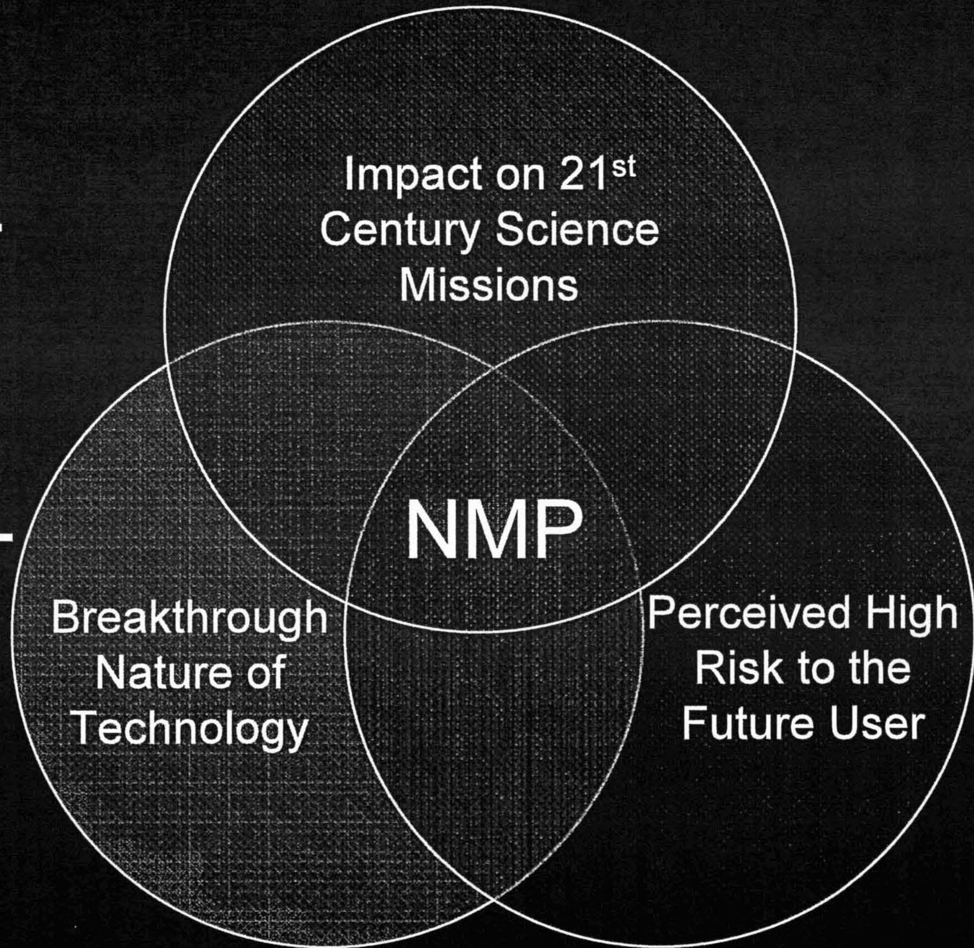
www.nasa.gov

New Millennium Program

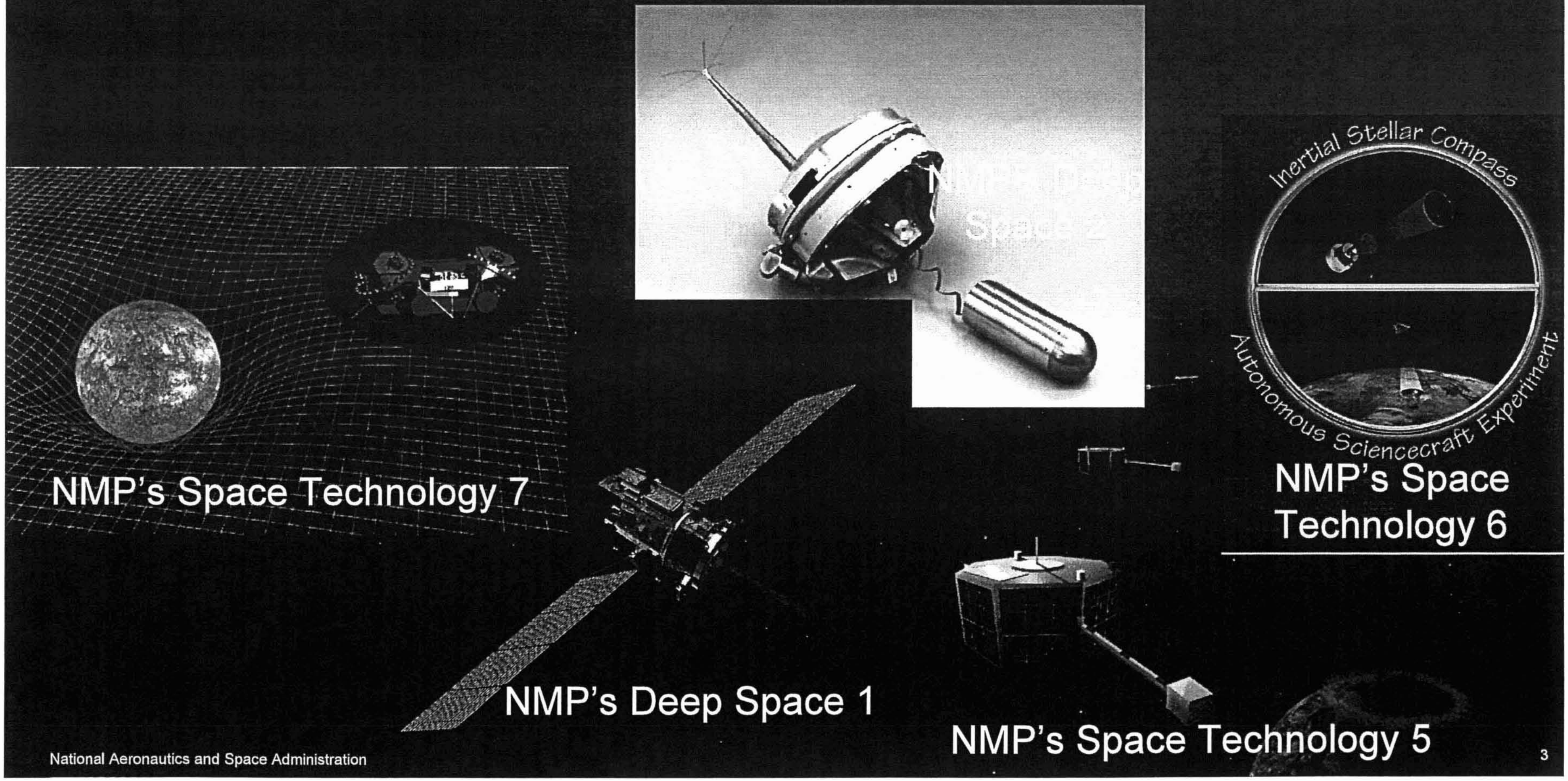
- NASA's New Millennium Program (NMP) exists to advance technologies with promising potential for use on future science missions.
- The NMP will soon select a proposed advanced technology to be incorporated into its Space Technology-9 (ST9) system-level flight validation experiment.
- Aerocapture is one of five technologies vying for a flight on ST9.



New Millennium Program

- **Information concerning past and future NMP missions may be found at:**

http://nmp.nasa.gov

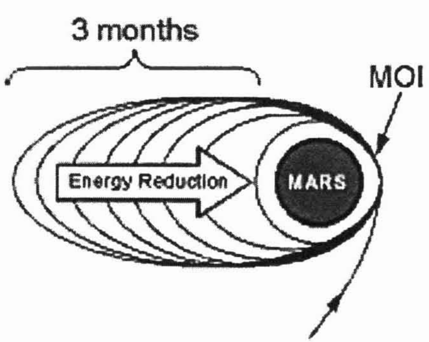


Aerocapture vs. Aerobraking

- **Aerobraking**
  - Propellant must be expended to establish the initial orbital insertion.
  - No heat shield is required, but satellite attitude provides maximum drag in upper atmosphere.
  - Approximately three months to establish final orbit.
  - Operationally intensive (each orbit requires atmospheric state monitoring, drag calculation, and precise location).
  - Used to establish Mars orbit for:
    - Mars Odyssey (2001) and
    - Mars Reconnaissance Orbiter (2005).

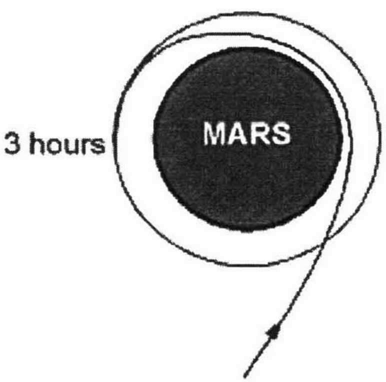
- **Aerocapture**
  - Intense atmospheric drag provides 95% of ΔV required to establish orbit.
  - Thermal protection system, heatshield/aeroshell, and jettison mechanisms add hardware mass to spacecraft, but save propellant mass.
  - Final orbit established in minutes versus months.
  - Used to deliver higher payload mass fraction of launched mass.
  - Proposed and developed for several missions, but never implemented.

Aerobraking



	Aerobraking	Aerocapture
Time to final orbit	**3 Months**	**3 Hours**
MSR S/C (kg)	900	900
Propellant (kg)	700	20
Aeroshell (kg)	N/A	180
Total arrival mass (kg)	**1600**	**1100**

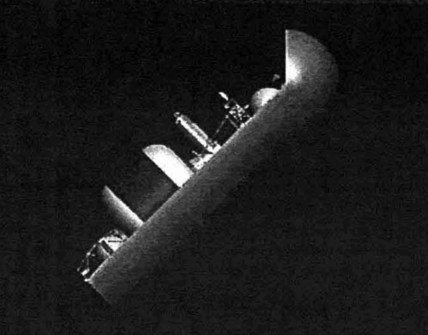
Aerocapture



Aerocapture Technology
Specific Architectures

Lower TRL

Designs	Trailing Ballutes	Attached Ballutes

- Moderate to high maturity for small bodies; low to moderate maturity for other planets
- Provides modest tolerance for nav and atmospheric uncertainties

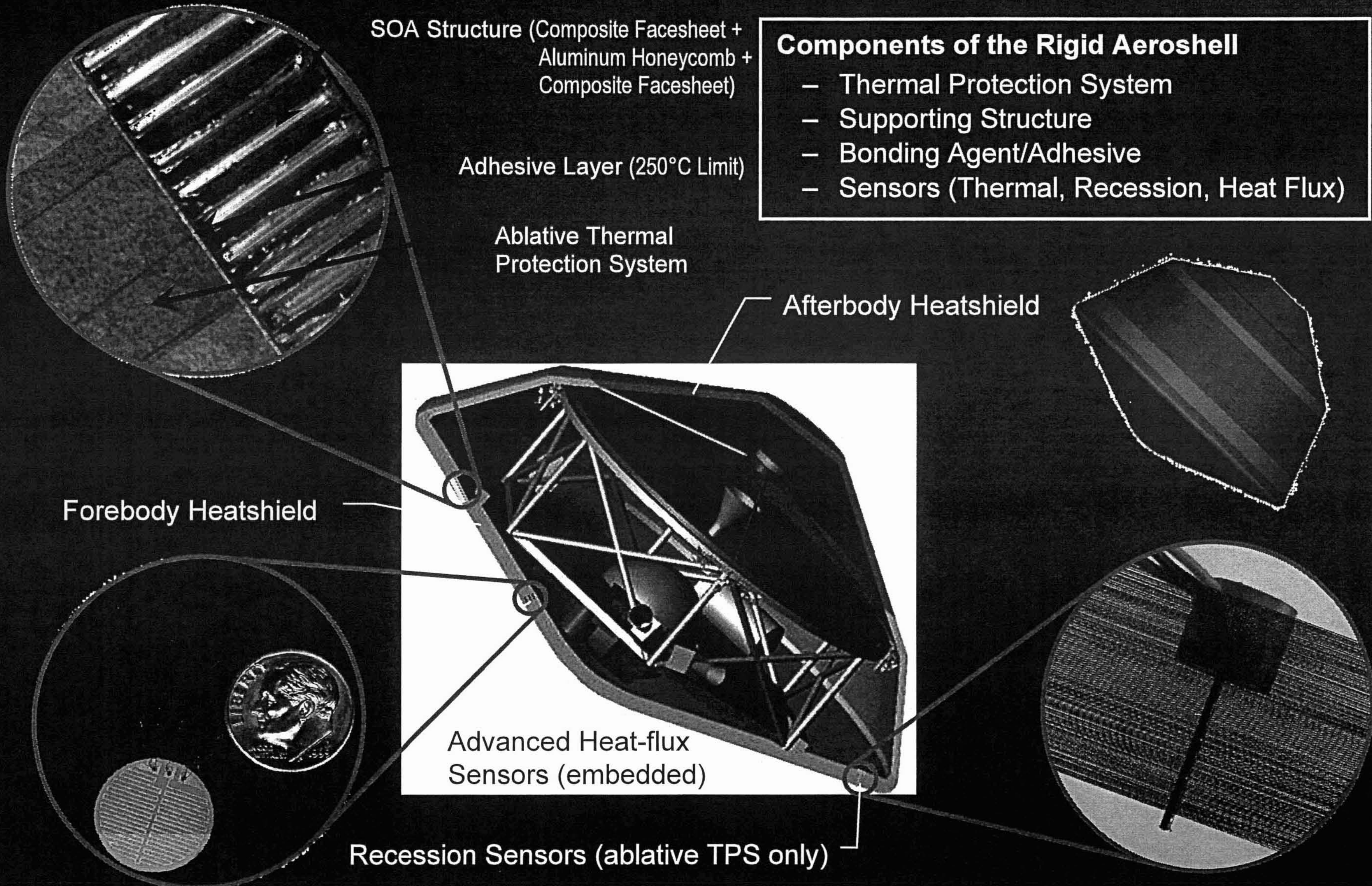
- Low to moderate maturity
- Provides increased tolerance for nav and atmos. uncertainties
- Design originally for human missions to Mars. Preliminary studies indicate that Slender Body Designs may be required for Neptune.
- Provides increased volume and improved packaging advantages for larger spacecraft.

- Low maturity
- Applicable to all size and shape payloads
- May have performance advantages over Blunt Body, such as not having the payload enclosed during interplanetary cruise

- Low to moderate maturity for Earth and Mars
- Developed and launched in 1996 by Soviet Union as part of Mars penetrator mission. Launch vehicle failure.
- Investigating feasibility of using aerodynamic lift for precision trajectory control
- Has potential volume and packaging advantage for larger spacecraft

The Rigid Aeroshell System

Components of the Rigid Aeroshell
- Thermal Protection System
- Supporting Structure
- Bonding Agent/Adhesive
- Sensors (Thermal, Recession, Heat Flux)



Aerocapture Benefits

- **The benefits of aerocapture as a method of orbital deceleration and capture are quantified through various cost/mass/benefit studies.**
- **Aerocapture provides a substantial mass advantage for most orbital missions to worlds with atmospheres when compared to alternative orbit insertion techniques.**
  - The aerocapture mass advantage is so large as to be enabling for many outer planet missions.

Comparison of Payload Mass Increase Using
Aerocapture vs. Best Non-Aerocapture
Method for Various Mission Scenarios*

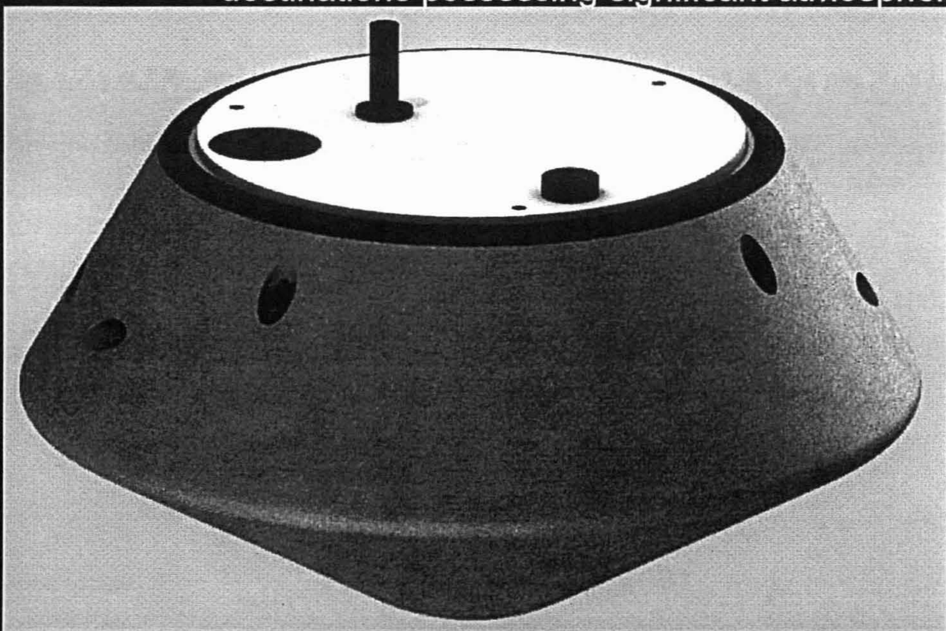
Destination	Working Orbit (km)	Nominal Inertial Entry Speed (km/s)	Orbit Insertion, ΔV (km/s)	Delivered Payload Mass Increase
Venus	300 (circular)	11.7	4.6	79%
Venus	8,500 x 300 (elliptical)	11.7	3.3	43%
Mars	300 (circular)	5.9	2.4	15%
Mars	37,000 x 300 (elliptical)	5.9	1.2	5%
Jupiter	2000 (circular)	59.0	17.0	Mission Enabling
Jupiter	1,880,000 x 1,000 (elliptical)	59.0	1.4	-51%
Saturn	120,000 (circular)	35.0	8.0	Mission Enabling
Titan	1,700 (circular)	5.9	4.4	280%
Uranus	450,000 x 4,000 (elliptical)	24.0	4.5	218%
Neptune	430,000 x 4,000 (elliptical)	29.0	6.0	832%

* J.L. Hall, M. A. Noca, and R.W. Baily, "Cost-Benefit Analysis of the Aerocaptrue Mission Set," *Journal of Spacecraft and Rockets*, Vol. 42, No. 2, Mar-Apr 2005.

New Millennium Program's Space Technology 9

Aerocapture Flight Validation Proposal

- **An Earth-based flight validation of the aerocapture maneuver is proposed for NMP's Space Technology 9 flight validation opportunity.**
- **The ST9 Aerocapture opportunity is scheduled for launch in June 2010.**
- **If aerocapture is the system technology selected for flight, the ST9 mission will flight validate:**
  - New, advanced technologies:
    - Guidance Navigation and Control System and
    - Thermal Protection Systems
    - (plus Advanced Sensors).
  - Aerothermal and aerodynamic performance models using the flight test data acquired through the fully instrumented high fidelity aeroshell sensor suite and internal navigation systems.
  - Aerocapture as a system technology for immediate infusion into future missions to Solar System destinations possessing significant atmospheres.

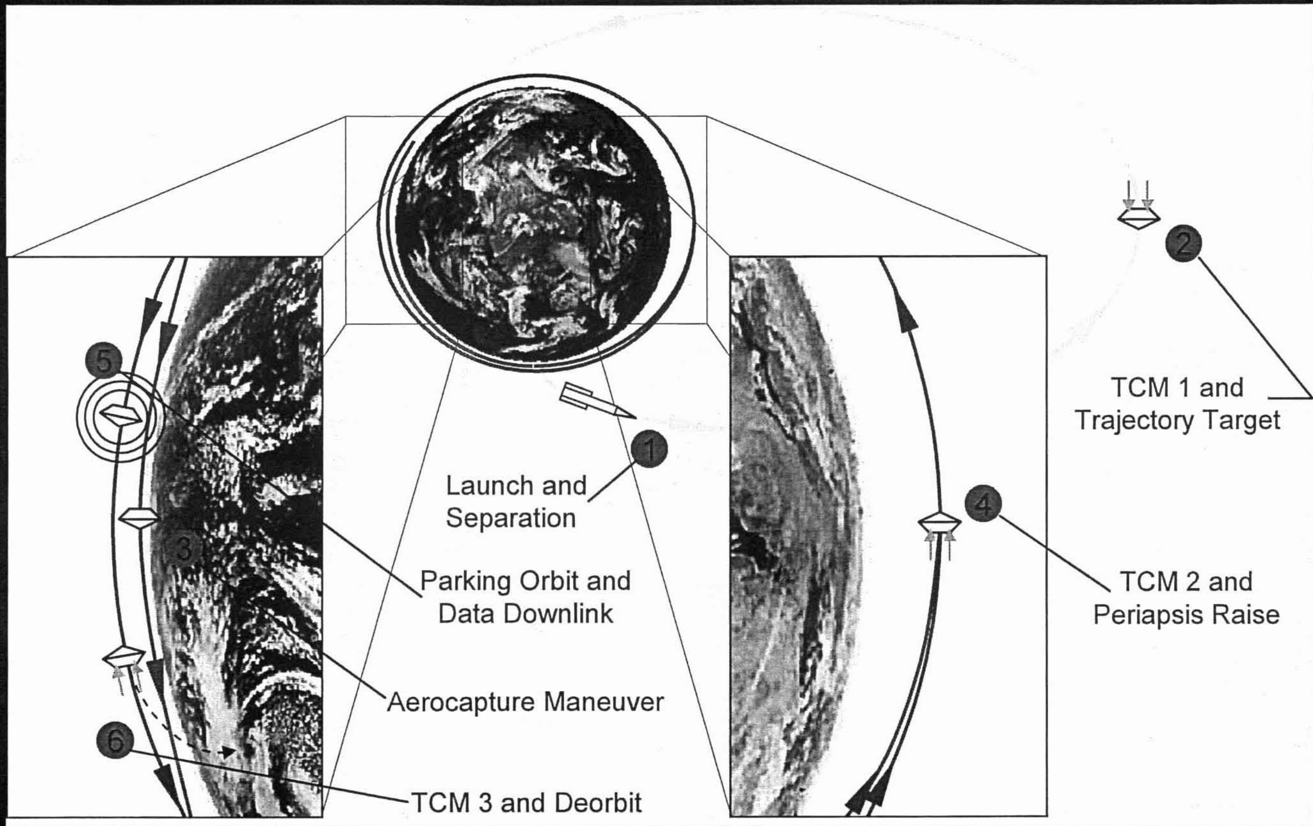


Proposed Teaming Arrangement

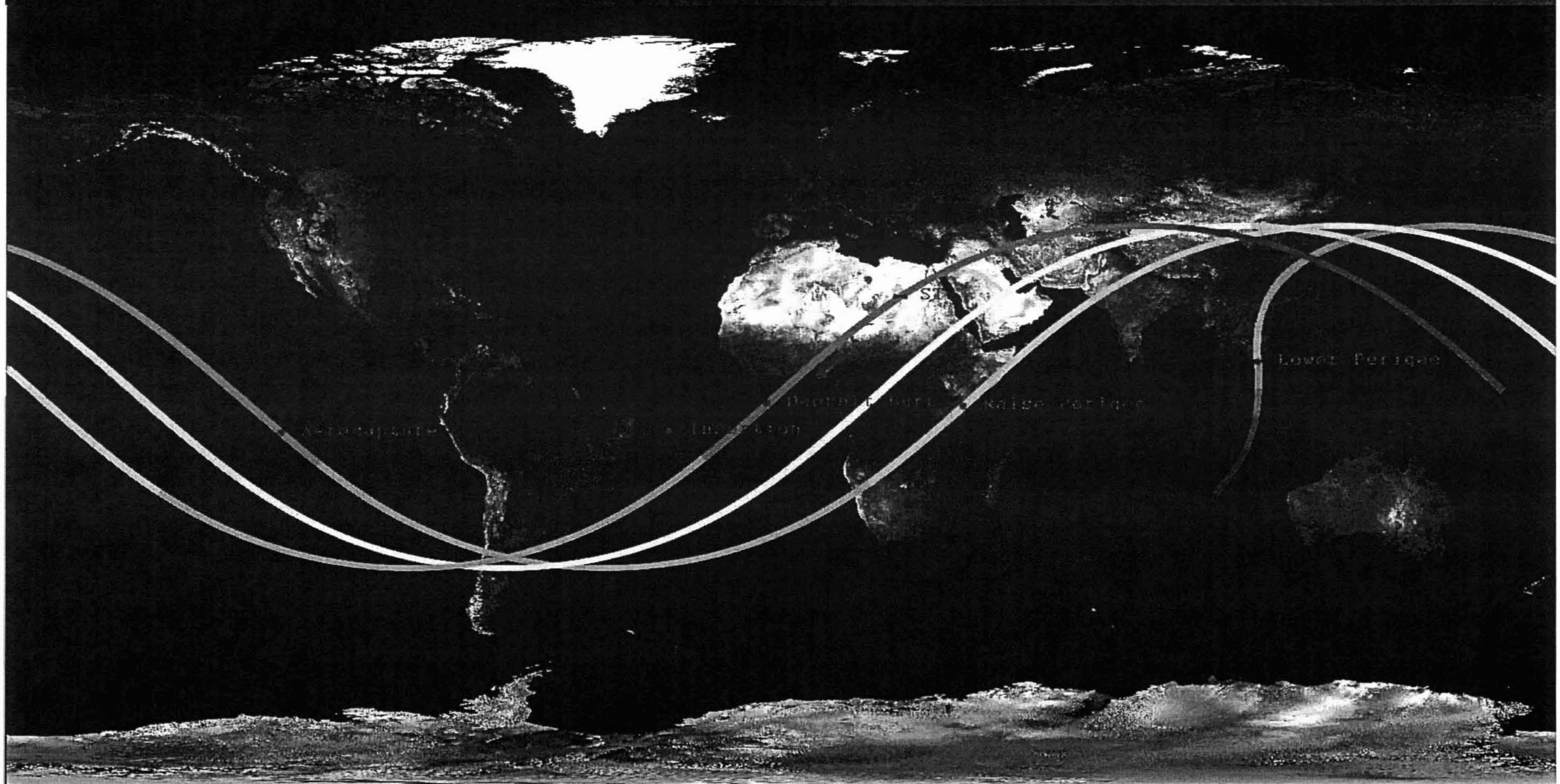
- **JPL:**
  - Lead center responsible for the aerocapture concept study and flight project implementation.
- **MSFC:**
  - Manages the In-Space Propulsion (ISP) Project, a programmatic partner responsible for managing and delivering the flight aeroshell subsystem.
- **LaRC:**
  - Responsible for trajectory simulations, aerothermodynamics, aeroshell verification and validation.
- **ARC:**
  - Responsible for aeroshell instrumentation, aerothermodynamics, and TPS testing, verification and validation.
- **Ball Aerospace:**
  - Provides the aerocapture guidance system and trajectory simulations.
- **Applied Research Associates Ablatives Laboratories:**
  - Provides the TPS materials, SRAM-20 and SRAM-14 for the forebody heatshield and aftbody backshell, respectively.
- **ATK Space Systems:**
  - Provides the aeroshell vehicle heatshield, backshell, structures and subsystem testing.
- **JSC:**
  - Aerocapture guidance verification and validation.

Proposed Mission Profile

- Aerocapture vehicle is launched on a Delta II as a secondary payload to GTO.
- As vehicle nears an orbital apoapsis of 20K to 36K km, the first trajectory control maneuver (TMC) is performed for precision atmospheric entry targeting.
- Aerocapture maneuver flown through a precision corridor as determined by the GN&C system.
- Second TMC performed to raise orbital periapsis and establish parking orbit.
- Downlink engineering and aerocapture performance data.
- Third TCM performed for safe deorbit of vehicle.



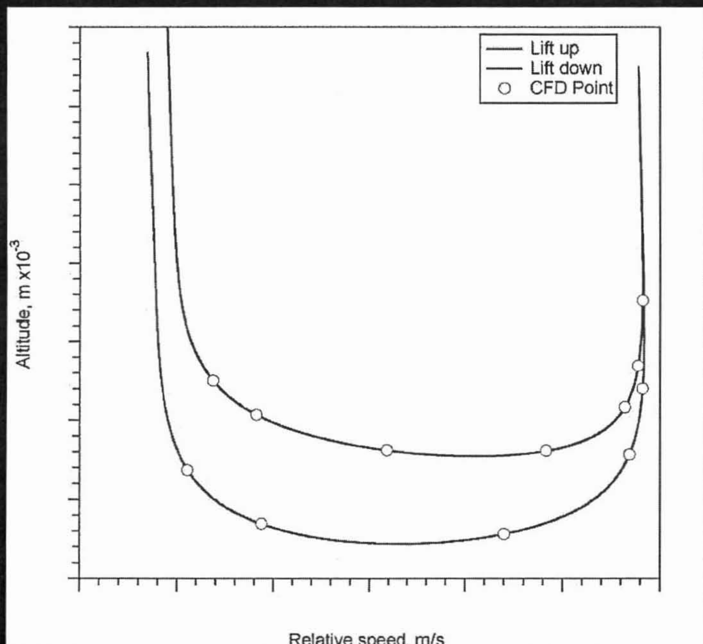
Representative Mission Groundtrack



Aerocapture Trajectory Corridor Predictions

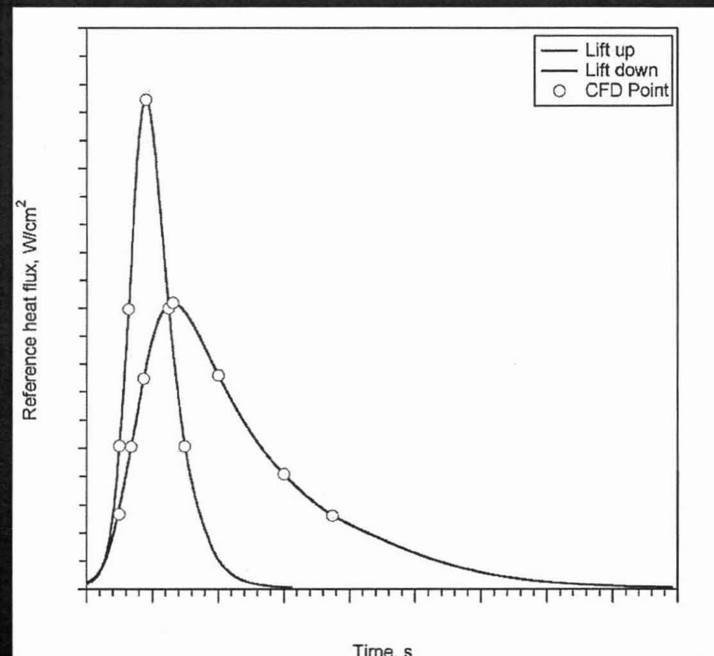
Predicted environmental parameters stated in terms of:

Altitude vs. Relative Speed



Predicted environmental parameters stated in terms of:

Heat Flux Experienced at the Heatshield Stagnation Point vs. Time



Both plots contrast the "lift up" trajectory corridor limit and the "lift down" trajectory corridor limit. Also shown are points (open circles) chosen for CFD point simulations of aerothermal environments.

Technology Advancement

- **System level objectives for the ST9 Aerocapture mission is to:**
  - Demonstrate satisfactory performance on the integrated flight vehicle during the aerocapture maneuver and
  - Acquire sufficient experimental data to validate and improve the efficacy of tools used for future mission and atmospheric design, simulation, and modeling.

- **The aerocapture maneuver is implemented as an onboard feedback control system with key elements:**

  (1) Aerodynamic lift providing mass efficient trajectory modulation,

  (2) Attitude control thrusters,

  (3) Vehicle state information via inertial measurement unit,

  (4) Guidance, Navigation and Control (GN&C) software receiving state inputs and providing vector outputs, and

  (5) A supporting aeroshell and spacecraft system providing a thermal protection system (TPS) and spacecraft envelope shape for aerodynamic force control.

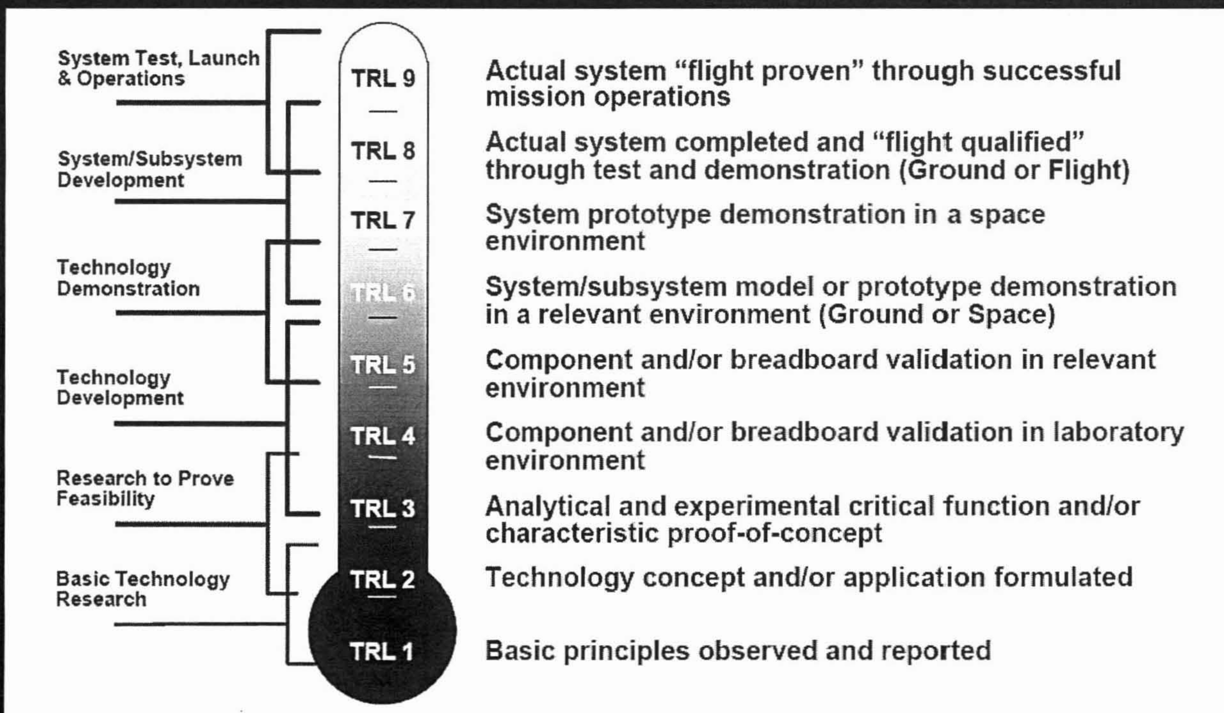
- **Technology maturation of (4) GN&C and (5) TPS materials will be flight validated aboard a ST9 Aerocapture mission.**

Technology Readiness Level

To ensure that any new advanced technology being proposed for a first flight is sufficiently mature, the NMP employs a technology rating standard, known to NASA as the

Technology Readiness Level

rating to assist with the assessment of a technology's maturation and test.

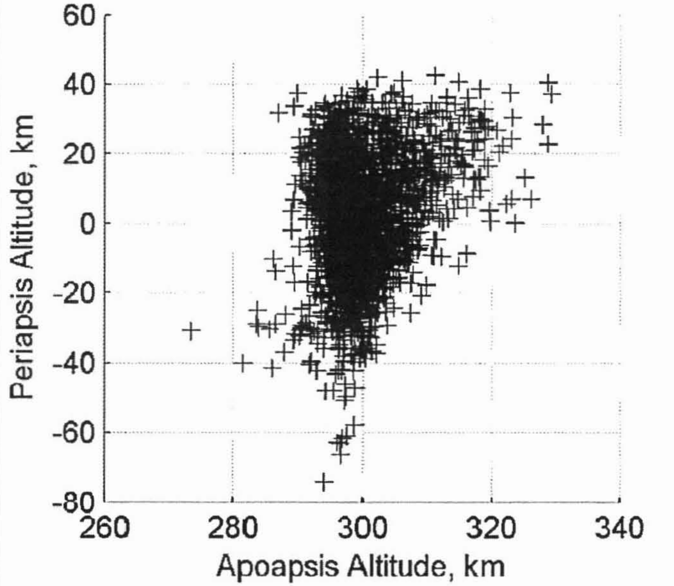


NMP guidelines state that the technology advances to be realized by the spaceflight validation experiments are to be at:

- TRL4 by the end of the Concept Development Study Phase of the project (current)
- TRL5 by the end of the Formulation Refinement Phase (Feb. '08)
- TRL6 by the start of the Assembly, Test, and Launch Operations Phase (Jun. 09)

Aerocapture Guidance Algorithm Description

- **The proposed GN&C system:**
  - Targets a lifting vehicle through the atmosphere to a desired exit orbit apoapsis and inclination (or plane) through rotation about velocity vector (bank angle)
    - Vertical component of lift vector controls altitude rate to target desired apoapsis
    - Lateral component of lift vector causes orbit plane change
    - Periodic bank reversals keep orbit inclination (or wedge angle) error within desired limits.

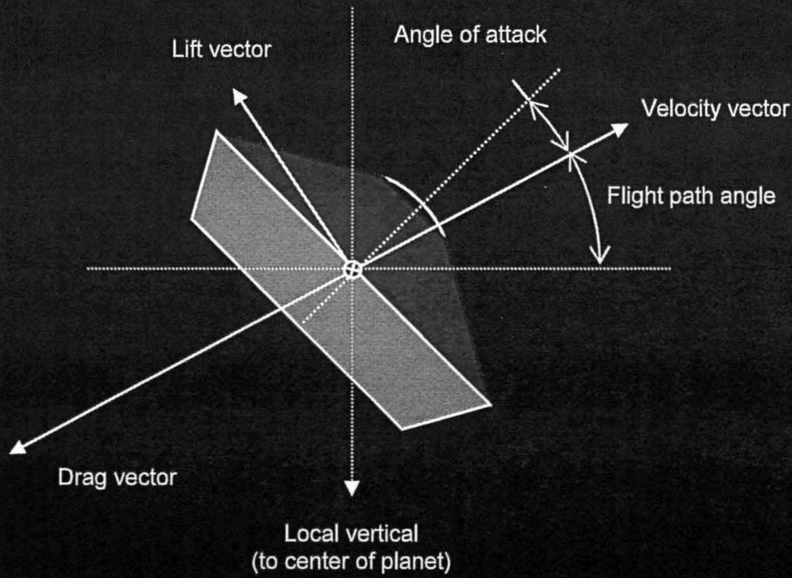


Monte Carlo Simulation Runs

- **Key GN&C algorithm features include:**
  - Independent of vehicle scale, lift-to-drag ratio, and ballistic coefficient
  - Applicable to all destinations in our solar system with appreciable atmospheres
  - Automatic compensation for large variations in the atmosphere density profile as well as random density perturbations
  - Automatic compensation for variation in vehicle aerodynamic parameters
  - Ability to capture nearly 100 percent of the theoretical entry corridor (providing robustness to entry delivery errors)
  - Tolerance to navigation system errors during aerocapture flight

Aerocapture Guidance Algorithm Description

- **Aerodynamic drag provides the DV, while aerodynamic lift provides capability required to respond to dispersions**
  - When more drag is required → lift vector down pulls the vehicle deeper into the atmosphere where the density is higher
  - When less drag is required → lift vector up to fly higher (lower density and drag)
- **Navigation uses a fixed lift vector that is pointed in different directions by rotating the vehicle with thrusters about the velocity vector (bank angle modulation)**
- **The guidance software works with the rest of the feedback control system (sensors, thrusters) to control the lift vector orientation as a function of time so as to precisely target the orbit upon exiting the atmosphere**
- **The aerocapture trajectory consists of the following:**
  - Entry targeting – Atmospheric entry angle must be within an upper and lower bound (theoretical entry corridor)
  - Arrest descent rate – Altitude rate goes from negative to zero
  - Dissipate energy – Fly at nearly constant altitude to dissipate excess energy
  - Exit atmosphere – Control altitude rate and velocity at atmospheric exit so as to achieve target orbit apoapsis
  - Periapsis raise – Automated propulsive maneuver to raise periapsis so that vehicle does not reenter atmosphere

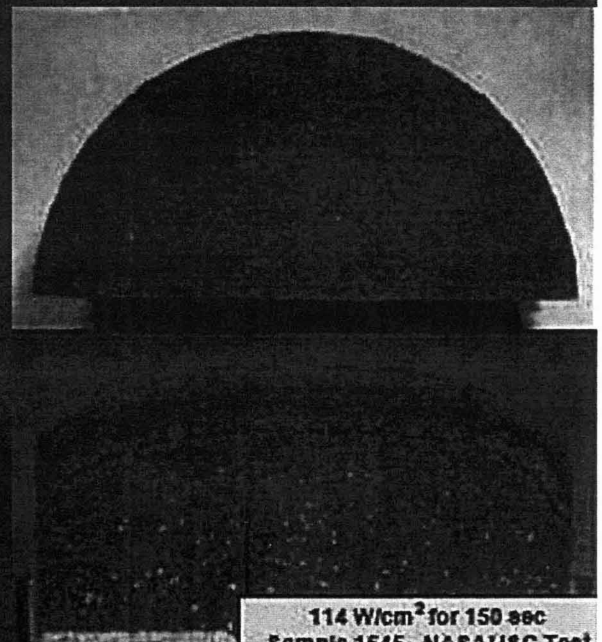


Thermal Protection System

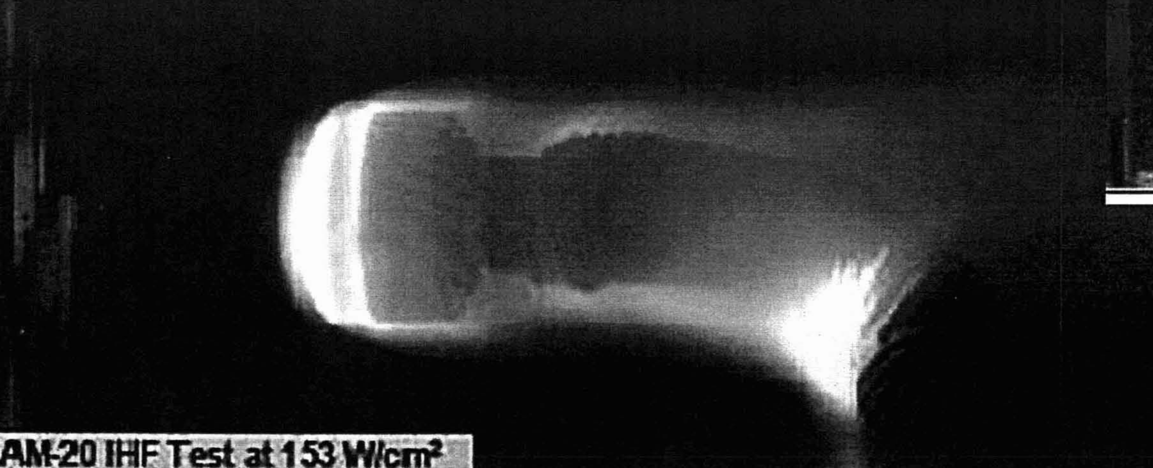
- **SRAM-20 and SRAM-14 are the TPS materials selected to protect the flight vehicle during the aerocapture maneuver.**
- **These two materials are members of the SRAM family of silicone ablators.**
- **They demonstrate high potential for thermal protection of not only the ST9 flight vehicle, but also any number of proposed NASA entry vehicles for missions to Mars, Venus, Titan, and Earth return.**
- **The material family possesses qualities of:**
  - lightweight mass,
  - low thermal conductivity,
  - intrinsic oxidation resistance, and
  - relatively uncomplicated manufacturing.
- **Densities range from 0.22 g/ cm3 to 0.38 g/cm3.**

SRAM-20

- SRAM-20 was selected as the forebody acreage TPS material because it possesses the proper balance of mass and performance for the predicted ST-9 heating environment.
- SRAM-20 has high efficiency for peak heating up to 300 W/cm2 and can accommodate short term exposures up to 400 W/cm2.
- SRAM-20's thermal-ablation response model includes:
  - in-depth pyrolysis,
  - transpiration cooling, and
  - thermochemical surface recession.
- SRAM-20 is currently undergoing arc jet testing at NASA's Ames Research Center.
- SRAM-20 is an excellent choice for many new missions and herein rests the impetus for flight validation on the proposed ST-9 flight.



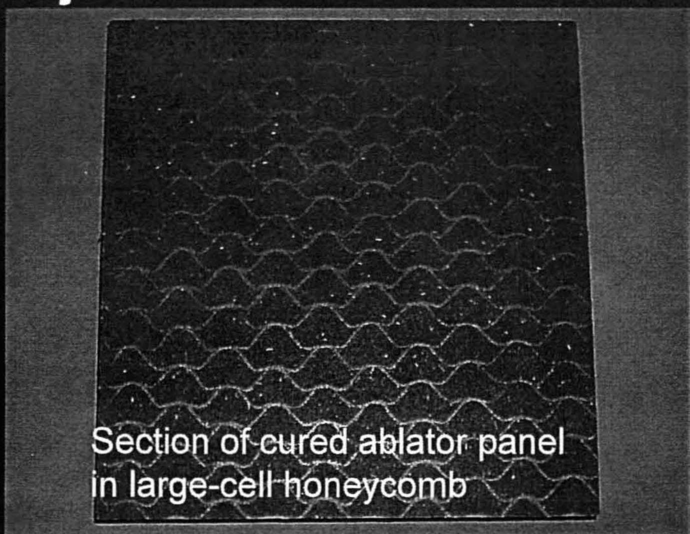
114 W/cm^2 for 150 sec
Sample 1545 - NASA/JSC Test



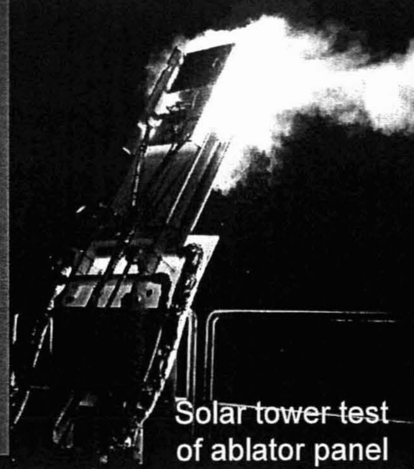
SRAM-20 IHF Test at 153 W/cm^2

SRAM-14

- In contrast to the harsh environmental heat loads and pressures experienced by the flight vehicle's heatshield, the backshell will be in the flight vehicle's wake and will thus experience a more benign environment.
- However, the backshell still requires a TPS to thermally protect the flight vehicle.
- SRAM-14 was selected to cover the aftbody backshell.
- SRAM-14 is much like its sister material SRAM-20 in that is also a lightweight silicone ablator, but is slightly different in composition; making it lighter in weight and less tolerant of high heat loads.
- Like SRAM-20, SRAM-14 is also undergoing environmental testing in the arc jet facilities of NASA's Ames Research Center.



Section of cured ablator panel in large-cell honeycomb



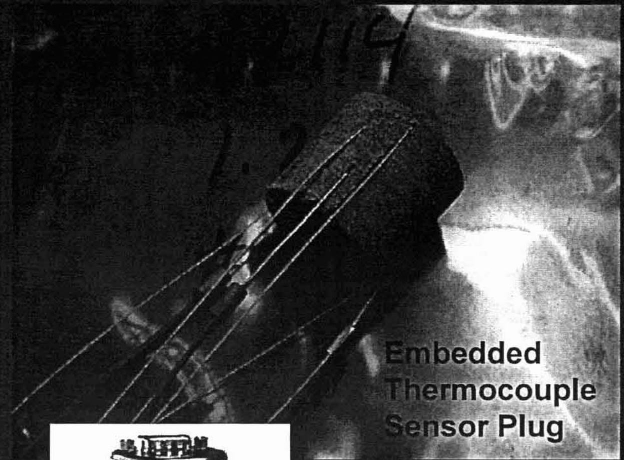
Solar tower test of ablator panel

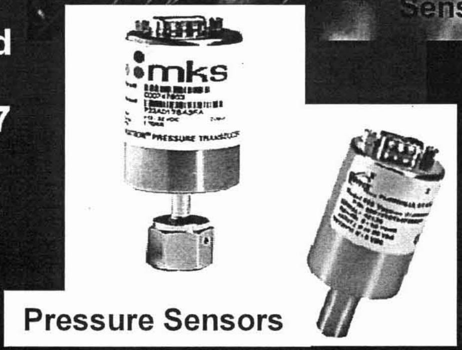
Solar tower test of ablator coupons

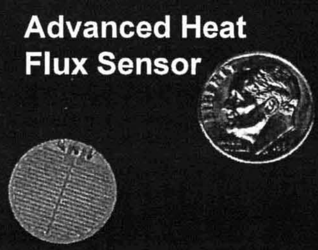
Advanced Sensors

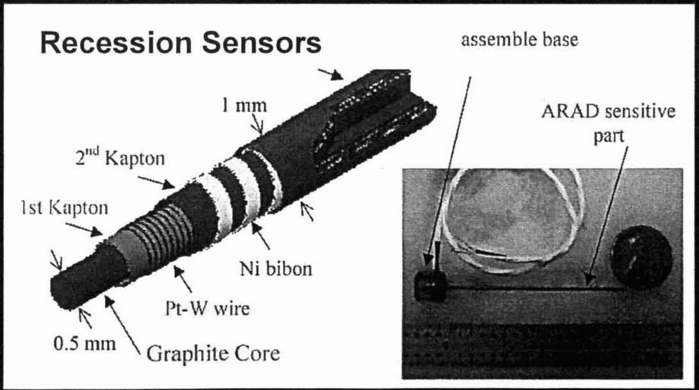
- **The ST-9 aerocapture validation experiment is unique among atmospheric entry vehicles in that, if selected, it will be the most heavily instrumented atmospheric re-entry vehicle ever flown.**
- Without instrumentation, ST9 is a "pass/fail" experiment, not a validation
  - **In order to "validate" the aerocapture maneuver, we must show that we accurately predicted the behavior of the vehicle during its flight, not just that it achieved its final orbit.**
- **The flight vehicle will use a vehicle state, flowfield and heatshield response instrumentation system based on a mix of TRL 9 components and TRL 6-7 advanced sensor components.**
- **This system will consist of:**
  - an IMU,
  - a series of pressure ports in the forebody of the vehicle in the configuration of a Flush Air Data System,
  - aftbody pressure sensors,
  - embedded thermocouples,
  - material recession sensors, and
  - heat flux gauges.

  - An optical spectrometer is also baselined to provide verification of the relative amounts of chemical constituents encountered in the shock layer.



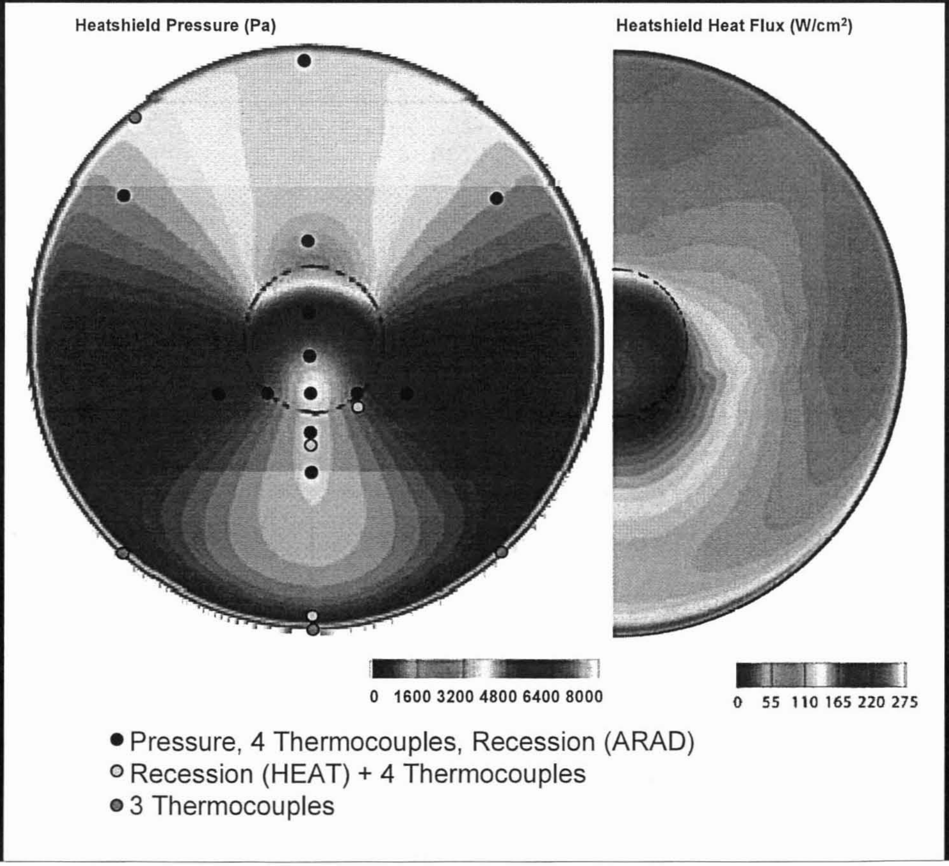






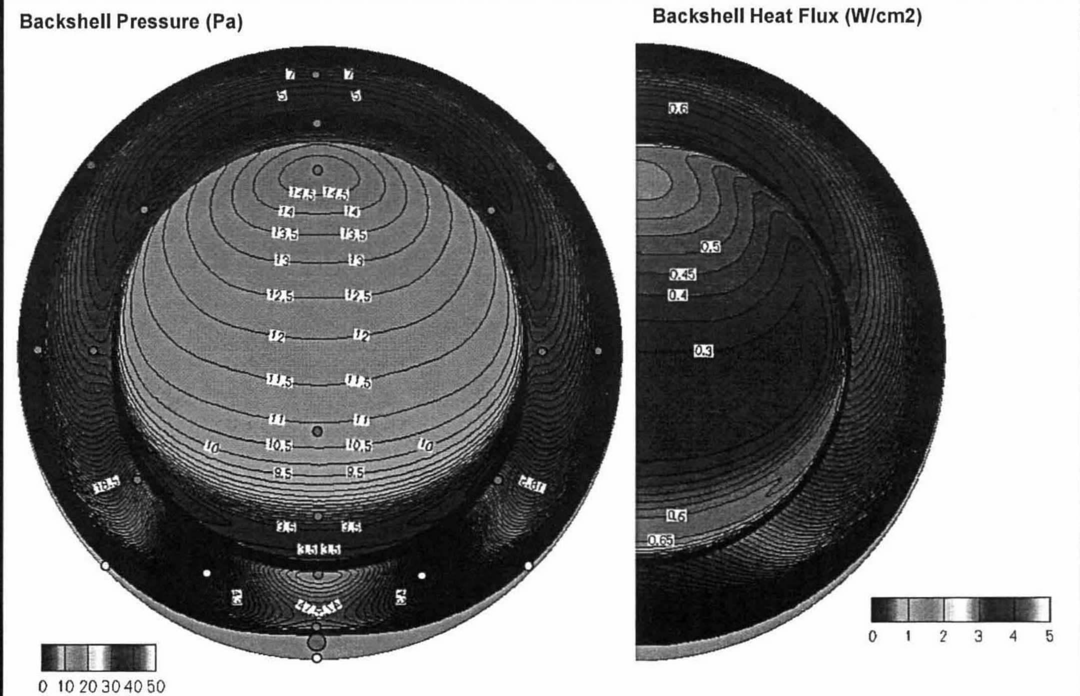
Forebody Sensor Placement

- These sensors are specifically positioned to measure temperatures, pressures, and recession rates of the TPS material at various locations on the forebody heatshield.
- The data collected by the sensor suite will be used to validate ground-based model predictions and the performance of the guidance system.



Aftbody Sensor Placement

- **These sensors are specifically positioned to measure temperatures, pressures, and recession rates of the TPS material at various locations on the aftbody backshell.**



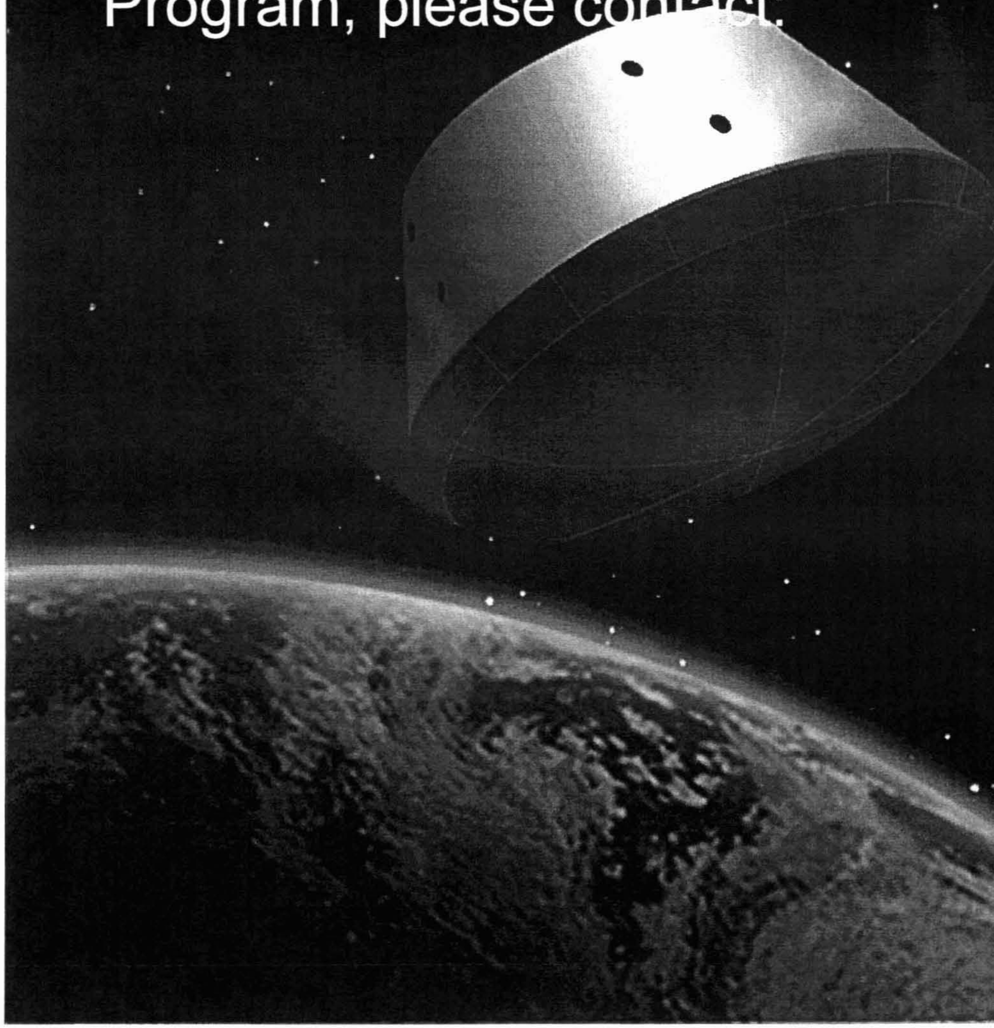
- Catalysis, 2 Thermocouples
- 1 Pressure, 2 Thermocouple (1 Pressure, 1Thermocouple, 1 Heat Flux on Plate)
- 2 Thermocouple, 1 Recession (ARAD)
- 2 Thermocouple, 1 Heat Flux
- Spectrometer

Conclusion and Summary

- **Aerocapture is a very useful capability for NASA that can be used across a wide range of planetary mission sizes and destinations.**
  - A substantial mass advantage may be realized through aerocapture maneuver implementation.
  - The mass advantage is enabling for certain outer planet mission profiles.
  - Aerocapture technology provides corollary benefits to the related applications of atmospheric entry and precision landing on worlds with atmospheres:
    - Aero/aerothermaodynamic model validation,
    - Hypersonic guided flight
    - TPS materials
    - And performance model validation.
- **The ST9 Aerocapture flight validation will be sufficient to immediately infuse aerocapture technology into future NASA science missions**
- **The advanced technologies being flight validated will enable the system level goal of performing an aerocapture maneuver.**
  - GN&C System,
  - TPS materials, plus
  - Advanced recession and heat flux sensors.

Contact Information

For additional information on the Aerocapture Technologies task area within the In-Space Propulsion Technology Program, please contact:



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